An Introduction to Optical Window Design

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Abstract

The purpose of this paper is to give the practicing engineer a practical introduction to the area of optical window design. Several design considerations and typical specifications for optical windows and their mounting are discussed. Several examples taken from literature are referenced and used to illustrate modern optical window design. Mathematical models used for design of pressure rated plane windows are also discussed.

Introduction

The purpose of a window as an element in an optical system is to provide a clear aperture to transmit the desired radiation and to keep the two environments separate. A window may also be used to keep any gases present in the two environments separate as well as bear any atmospheric differences such as temperature and pressure. A thorough introductory discussion on optical windows can be found in Yoder's *Opto-Mechanical Systems Design* including mounting of plane windows and domes, structural considerations, and optical performance degradation[1]. Yoder summarizes the critical considerations for window design including mechanical and thermal distortions and sealing technique. Proximity of the window with respect to the aperture stop or pupil becomes important when designing for minimal wavefront degradation.

Window Materials

Table 1 (adapted from Red Optronics[2]) shows a summary of optical window materials and their important properties including transmission range, index of refraction, and their typical applications. Often it is best to find the manufacturer's data on the type of window material they supply. The table shows that BK7 glass is the most common and is only substituted for when there are special requirements of the optical system.

Table 1. Common Window Materials

Window Material	Transmission range	Index of refraction	Applications
BK7	330-2100 nm	1.5164 @ 588 nm	-most common -low cost
Fused Silica	185-2500 nm	1.4858 @ 308 nm	-UV to IR spectrum -Best choice for thermal resistance application; low CTE: 0.54 ppm/K
Sapphire	180-4500 nm	1.755 @ 1000 nm	-best choice for scratch resistance applications -thinner optics -wide transmission range
Calcium Flouride	170-7800 nm	1.399 @5000 nm	-IR laser applications -low hygroscopic susceptibility
MgF2	120-7000 nm	1.376 @ 700 nm	-UV laser applications

Window Performance Specification

Optical windows usually consist of two flat surfaces and have negligible effect on collimated light, but may affect non-collimated beams by introducing aberrations. However when windows are thin, they usually impart little to no system level degradation. Wavefront errors are a result of index variation and surface imperfections left by the manufacturing method. A typical window performance specification includes the allowable deterioration of a plane wavefront through the entire aperture of the window. This allowable deterioration varies depending on the system application and can vary from 1 wave peak to valley (P-V) at 0.63 µm for a viewing window all the way down to 0.05 wave P-V at 0.63 µm for a high performance photographic system[1].

Vukobratovich presents an equation to evaluate the approximate optical path difference created by a simply supported, round window deformed by a uniform load ΔP_W on its face[3]. The unsupported aperture diameter is given as A_W.

$$OPD = 0.00889(n-1)\Delta P_W^2 A_W^6 / \left(E_G^2 t_W^5\right) \qquad \text{(Yoder 6.3)}$$

E_G is the Young's modulus and n is the refractive index of the specific window material. Vukobratovich also stated that if the window is subjected to acceleration a_G, the following could be substituted into the above equation for ΔP_W:

$$\Delta P_W = a_G \rho_G t_W \qquad \text{(Yoder 6.5)}$$

Where ρ_G is the window material density and t_W is the thickness of the window[3].

Typical Window Mounts

Yoder gives an example of a typical window mounting technique which can be seen in Figure 1. It consists of a round glass element held in place by MIL-S-11031 adhesive which is injected through holes as the window is held in place. The housing for the window is 303 stainless steel and has a threaded outer diameter for mounting. Often, since plane windows do not have an optical axis, the clearances between the window and the housing is large enough to remain economical and easy to assemble. The example given by Yoder in Figure 1 has a 50.8 mm diameter window and there is a 0.22 to 0.53 mm clearance between the mating cylindrical surfaces[1].

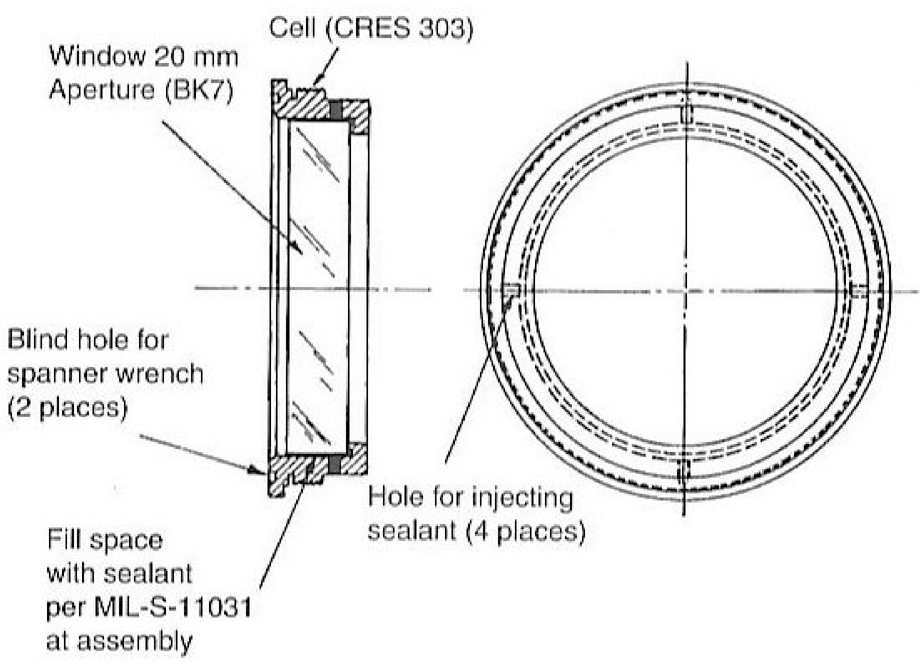

Figure 1. Bonded-in-place glass instrument window (Yoder, Fig. 6.1)[1]

Another method for mounting windows is to create geometry that provides a clamping force to hold the window in place. Often this technique includes soft gasketing that seals against the window as it is compressed. This can be used in conjunction with the technique seen in Figure 1 by means of a clamping ring. Suitable materials for the barrel and clamp can include brass, aluminum, and steel.

Figure 2 shows two examples of acrylic plane plate windows used in high pressure, deep underwater structures. The upper configuration consists of a 90° conical shaped window element clamped in place and cushioned with a neoprene gasket. The lower configuration in Figure 2 consists of a window with a machined groove to accept a sealing o-ring. A retaining o-ring holds the window in place at low pressures. Dunn and Stachiw studied the thickness to aperture diameter relationship and determined that the conical interface windows increase in strength as the cone angle increases from 0° but as it approaches 90° the two configurations failed at very similar critical loadings[4].

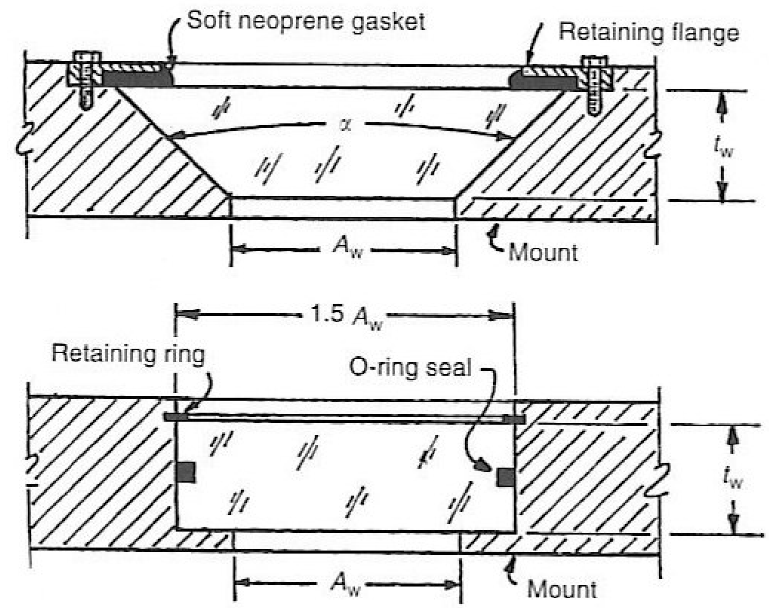

Figure 2. High pressure windows for deep submergence vehicles (Yoder, Fig. 6.29, adapted from Dunn, G., and Stachiw, J., SPIE, 7, D-XX-1,, 1966.)[4]

Strength of Windows

Much research has been done to study the mechanical strength and survivability of optical windows. When a window is subjected to large pressure differentials or accelerations or even if it is large and is subjected to high body force loads, a serious study of appropriate materials and sizes is necessary. Also, different approaches are taken to mount the window and distribute the resultant edge forces to reduce tensile stress. It is well known that glasses in general are particularly prone to tensile stress failure.

Yoder[1] adopts an equation from Harris[5] that gives the minimum thickness t_W for a circular plane window with unsupported aperture diameter A_W subjected to a uniform differential pressure ΔP_W :

$$t_W = 0.5 A_W \left[K_W f_s \frac{\Delta P_W}{S_F} \right]^{1/2} \qquad \text{(Yoder, 6.1)}$$

The factor of safety f_s is typically 4, and K_W is a support condition constant that is equal to 1.25 if the window is unclamped and 0.75 if it is clamped around the entire aperture. This makes intuitive sense, as an unclamped window would need to be thicker than a clamped window if subjected to the same pressure differential. Therefore as a rule of thumb, an unclamped window needs to be approximately 67% thicker than a clamped window. An example of each type of mount can be seen in Figure 3. When potting using RTV or other flexible adhesive, the window is considered unclamped. The material fracture strength S_F for several infrared window materials is given by Harris and appears in Table 2[5]. The fracture strength for many other types of optical glass can often be found in literature published by glass manufacturers such as Schott.

Table 2 (Yoder, Table 6.1)[4]

Typical Minimum Values for Fracture Strength S_F of Infrared Window Materials[a]

Material	S_F (MPa)	S_F(lb/in.^{2})
MgF_2 (single crystal)	142	2.05×10^4
MgF_2 (polycrystalline)	67	9.71×10^3
Sapphire (single crystal)	300	4.35×10^4
ZnS	100	1.45×10^4
Diamond (CVD)	100	1.45×10^4
ALON	300	4.35×10^4
Silicon	120	1.74×10^4
CaF_2	100	1.45×10^4
Germanium	90	1.30×10^4
Fused silica	60	8.70×10^3
ZnSe	50	7.25×10^3

[a] These values are approximate. They depend upon the quality of the surface finish, fabrication method, material purity, type of test, and size of the sample. *Source*: Adapted from. Harris, D.C., *Materials for Infrared Windows and Domes, Properties and Performance*, SPIE Press, Bellingham, 1999.

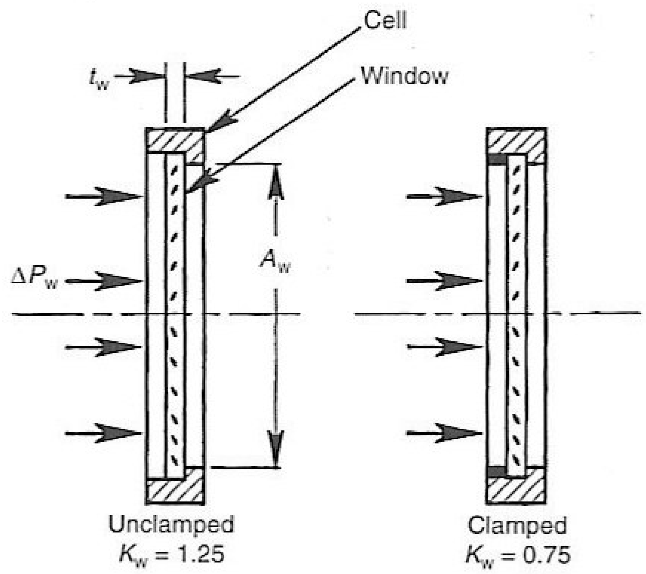

Figure 3. Unclamped ($K_W = 1.25$) and clamped ($K_W = 0.75$) window configurations (Yoder, Fig. 6.29, adapted from Harris, D.C., *Materials for Infrared Windows and Domes, Properties and Performance*, SPIE Press, Bellingham, 1999.)[5]

Sometimes special consideration must be made which might prevent the use of conventional sealants and gaskets. Manuccia et. al. describe a design of a 7.6 cm diameter sodium chloride (NaCl) window, 0.9 cm thick[6]. The window was designed to withstand an internal pressure of a few millitorr against normal atmospheric pressure outside. The design was used in an application where helium gas was irradiated with pulsed laser radiation and no sealants were therefore allowed. Instead, malleable lead gaskets are used on both sides of the window as well to form a seal. Bolts and Belleville washers are used to provide constant axial force while allowing radial expansion and contraction due to thermal shock. When the bolts are tightened, the lead gasket on the outer surface of the window is crushed into the microscopic geometry of the NaCl and a seal is formed. On the inner surface a similar lead gasket is crushed onto an inner flange and deformed to its shape forming a second seal. The combination of the lead and Teflon gaskets act to cushion the window as well as deform and ensure the spreading of preload over the clamping area.

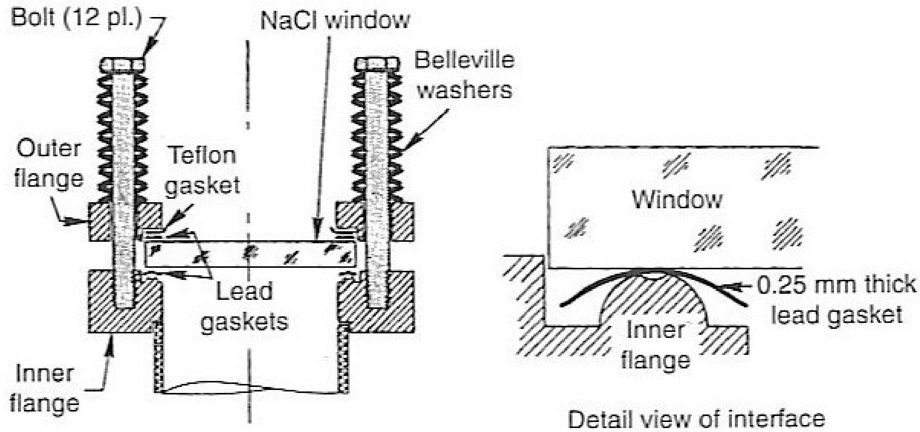

Figure 4. NaCl window for high vacuum IR system (Manuccia et. al., adapted by Yoder)[6]

Characterizing Strength of Optical Glass

Other factors are often taken into consideration when designing optical windows subjected to high loads such as surface imperfections, internal stresses, and the nature of the load (static or dynamic). Doyle and Kahan outline several methods for practicing engineers to use to determine the strength of optical glass according to its surface finish, glass type, and environment[7].

One design consideration that is presented by Doyle and Kahan is the fracture toughness of the glass. Fracture toughness in a material is its resistance to crack growth when under tensile stress. The glass fails when the stress intensity factor K_1 due to a crack, exceeds the fracture toughness of the material, K_{IC}. The stress intensity factor can be calculated using Griffith's law given by Doyle and Kahan as:

$$K_I = Y\sigma\sqrt{a} \qquad \text{(Doyle and Kahan 2.2)}$$

where Y is a crack geometry factor, σ is the nominal stress, and a is the crack, or flaw size. Fracture toughness for several optical glass types is given in Table 3 below[7].

Table 3. Glass fracture toughness values[7]

Fracture Toughness, K_{IC}	psi $\sqrt{\text{in}}$
Fused Silica	674
BK7	774
SF5	519
SK16	710
LaK10	865
F2	500
SF58	346

Conclusions

1. Optical windows at the outset seem like a simple design task but when they are used in applications with any amount of special requirements, careful attention to details of the design is in order.
2. Sealing optical windows can be accomplished with flexible silicone based adhesives such as RTV and aided with clamps. However, when requirements prohibit the use of conventional sealants, other methods and materials must be used such as the lead gasket example discussed here.
3. Windows subjected to high pressures can be designed using guideline formulas discussed here and appropriate safety factors.
4. The strength of optical glass involves understanding not only the basic material strength properties but also the surface quality, inclusions and the loading cycle of the window.

References

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3. Vukobratovich, D., Introduction to Opto-Mechanical Design, *SPIE Short Course* SC014, 2003.
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7. K.B. Doyle, M.A. Kahan, "Design strength of optical glass," *Optomechanics 2003*, Proc. SPIE 5176 (2003).